

FINAL TECHNICAL REPORT

Contrail-Cirrus Studies at FARS

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STATED RESEARCH OBJECTIVES

Our three primary goals have been to: 1) increase our contrail remote sensing database collected from the Facility for Atmospheric Remote Sensing (FARS) by expanding our Project FIRE Extended Time Observations (ETO) program to include contrail persistence studies: 2) continue our retrospective analyses of the statistical, physical, and radiative properties of contrails derived from our 10-year ETO cirrus cloud dataset to examine their potential direct impact for regional climate change: and, 3) prepare our mobile remote sensing systems and participate in the SUCCESS field campaign from the DOE Southern Great Plains ARM CART site.

## RESEARCH RESULTS

### 1. Extended Time Observation (ETO) studies at FARS

Over the two-year project period, we collected several dozen vertically-pointing polarization lidar, infrared radiometer, and surface radiation budget case studies of contrails, including several cases that appeared to produce extensive cirrus sheets from spreading contrails, significantly adding to our ETO contrail database. This was facilitated by significantly increasing the amount of morning observation periods at FARS, which local FAA jet traffic control information (and visual observations) revealed more favorable for contrail studies because of diurnal flight patterns in our region. Analysis of this data is described below.

### 2. Retrospective analyses

We analyzed the growing contrail remote sensing dataset from FARS and previous aircraft-supported field campaigns to shed light on several fundamental contrail properties, as reported in Sassen (1997a, attached as Appendix A). We have established the local monthly frequency of contrail occurrence, measured with lidar their heights and with local radiosonde data their environmental temperatures and relative humidities, and determined their range of radiative impacts in the visible and infrared spectral regions using lidar, midinfrared radiometer, and solar tracking radiometers. Significant findings to date are that contrails are exclusively generated at temperatures colder than  $-35^{\circ}\text{C}$  from the homogeneous freezing of condensed droplets, appear in many cases to persist for extended periods in sub-ice saturated air (i.e., at or above 85-90% relative humidity with respect to ice), and can dramatically reduce the amount of incoming solar radiation and, under favorable contrail growth conditions, increase the downwelling midinfrared radiation. The greenhouse effect in contrails, however, appears

to be outweighed by the solar albedo effect in many cases because of the relatively minute contrail particle sizes, leading us to conclude that any regional climatic changes induced by contrail-cirrus may act to counteract, for example, global warming from greenhouse gasses. This controversial conclusion, however, depends critically on the geographic and temporal (i.e., day-vs-night) distributions of contrails (see Sassen 1997a).

We have also made available selected FARS contrail case studies and in situ information to NASA collaborators to better understand the time evolution of contrail microphysical and optical properties (Sassen et al 1996; Khvorostyanov and Sassen 1997) and radar-scattering properties (Sassen and Khvorostyanov 1997) using 2D/3D cloud models; the radiative transfer consequences of small-particle contrails (Liou et al. 1997); and the effects of particle size on depolarization lidar estimation of particle size and type (Mishchenko and Sassen 1997)

### 3. Participation in SUCCESS

Prior to the SUCCESS campaign, we modified and installed a small X-band radar system on the scanning table of the mobile Polarization Diversity Lidar (PDL) system to provide a laser-shutdown capability for eye safety purposes if the PDL is scanned too close to project or other aircraft during contrail studies. The PC software for the radar-based laser safety interrupt, and for new PDL scanning routines tailored to contrail studies, were developed and thoroughly tested during our highly successful SUCCESS field campaign. We also contributed to the success of the experiment by updating NASA scientists on local cloud conditions and the status of ground-based remote sensor operations at the Southern Great Plains CART site, and helped guide NASA aircraft operations in the vicinity of the CART site through ground-to-air communications.

Although our analysis of our ground-based lidar and infrared radiometer data from the SUCCESS campaign is still underway, we have attempted to keep the research community well informed on our initial

findings through conference presentations (Sassen 1997b; Sassen and Hsueh 1997a,b; Sassen et al. 1997), and we were able to include unique high resolution lidars displays of a variety of contrails in our contrail review article for the *Bulletin of the American Meteorological Society* (Sassen 1997a). During the April 1996 SUCCESS field campaign, contrails were studied with the PDL principally on three occasions, ranging from new contrails produced by participating NASA aircraft to persisting contrails from commercial jet aircraft that had spread into an almost invisible cirrostratus sheet. What distinguishes these contrails from natural cirrus was their tendency to remain physically thin (50 - 300 m), generate strong laser depolarization, and produce solar corona, even an hour or more after formation. To satisfy these findings, the contrail-cirrus must have been composed of high numbers of small (20-30  $\mu\text{m}$ ) particles, which has important implications for understanding their radiative and climatic effects (Sassen and Hsueh 1997c).

These remotely sensed findings indicate that comprehending the contrail radiative/climatic problem may be more difficult than previously assumed. Rather than treating the contrail problem as a simple increase in the spatial coverage of *normal* cirrus clouds, as has previously been done, it is apparent that cirrus derived from contrails are often, if not typically, fundamentally distinct from natural cirrus cloud layers. Progress in spreading this knowledge to modelers has already been made (e.g., Liou et al. 1997; Khvorostyanov and Sassen 1997).

## **Publications Resulting from this Research**

- Khvorostyanov, V.I., and K. Sassen, 1997: A contrail case study with use of a microphysical cloud model: Surface cooling versus upper tropospheric warming. *Geophys. Res. Lett.*, (submitted).
- Liou, K. N., P. Yang, Y. Takano. K. Sassen, T. P. Charlock, and W. P. Arnott, 1997: On the radiative properties of contrail cirrus. *Geophys. Res. Lett.*, (submitted).
- Mishchenko, M. I., and K. Sassen, 1997: Depolarization of lidar returns by small ice crystals: An application to contrails. *Geophys. Res. Lett.*, (submitted).
- Sassen, K., 1997a: Contrail-cirrus and their potential for regional climate change. *Bull. Amer. Meteor. Soc.*, **78**, (in press, September issue).
- Sassen, K., and V. I. Khvorostyanov, 1997: Radar probing of cirrus and contrails: Insights from 2D model simulations. *Geophys. Res. Lett.*, (submitted).
- Sassen, K., and C. Hsueh, 1997c: Contrail properties derived from high-resolution polarization lidar studies during SUCCESS. *Geophys. Res. Lett.*, (submitted).

## **Conference Proceedings**

- Sassen, K., J. M. Barnett, and V. I. Khvorostyanov, 1996: "Radiative Properties of Contrails: Measurements and Simulations", International Radiation Symp., Fairbanks, Abstracts, pp. 29.
- Sassen, K., 1997b: "Ground-Based Remote Sensing Contrail Studies during SUCCESS", AMS 3rd Conf. on Atmospheric Chemistry, Long Beach, 2 pp (invited).
- Sassen, K., and C. Hsueh, 1997a: "High-Resolution Scanning Polarization Diversity Lidar Studies of Contrails during SUCCESS", Solar Radiation Interactions with Aerosols and Clouds, A.G.U., Baltimore, pp. 116 (invited).

- Sassen, K., and C. Hsueh, 1997b: "CART Remote Sensing Cirrus/Contrail Case Study Opportunities from SUCCESS", Conf. On the Effects of Aviation, Virginia Beach, NASA, Abstracts pp. 138.
- Sassen, K., C. Hsueh, and J. M. Barnett. 1997: "High-Resolution Scanning Polarization Diversity Lidar Studies of Contrails and Cirrus Clouds from the April 1996 IOP/SUCCESS Campaign", ARM Science Team Meeting, San Antonio, Abstracts pp. 37.